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[Title Page]

**Reversible Watermarking Method Based on Asymmetric-histogram
Shifting of Prediction Errors**

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Abstract

This paper tries to provide a new perspective for the research of reversible watermarking based on histogram shifting of prediction errors. Instead of obtaining one prediction error for the current pixel, we calculate multiple prediction errors by designing a multi-prediction scheme. An asymmetric error histogram is then constructed by selecting the suitable one from these errors. Compared with traditional symmetric histogram, the asymmetric error histogram reduces the amount of shifted pixels, thus improving the watermarked image quality. Moreover, a complementary embedding strategy is proposed by combining the maximum and minimum error histograms. As the two error histograms shift in the opposite directions during the embedding, some watermarked pixels will be restored to their original values, thus the image quality is

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further improved. Experimental findings also show that the proposed method re-creates watermarked images of higher quality that carry larger embedding capacity compared to conventional symmetric histogram methods, such as Tsai et al.'s and Luo et al.'s works.

Keywords: Reversible watermarking; histogram shifting; asymmetric selection function; prediction errors; multi-prediction scheme.

1. Introduction

Reversible watermarking, also known as lossless or invertible watermarking, is a technique to embed the watermark into a digital content in a reversible way. In recent years, reversible watermarking has become a research hotspot, due to its various applications such as identity authentication, content integrity verification and covert communication, leading to many methods being published. As of now, most of them can be classified into three categories: transform domain ([Khan, 2012](#)), compression domain ([Chang, 2009](#); [Yang, 2011](#)) and spatial domain methods ([Coltuc, 2011](#); [Coltuc, 2012](#); [Hong, 2012](#)). In those developed reversible methods, two main methods have been widely applied: the difference expansion-based ([Tian, 2003](#); [Alattar, 2004](#); [Kamstra and Heijmans, 2005](#); [Thodi and Rodriguez, 2007](#)) and histogram shifting-based methods ([Ni et al., 2006](#)), which were made even more popular since the prediction and interpolation technologies ([Tsai, 2009](#); [Sachnev et al., 2009](#); [Luo et al., 2010](#); [Hong and Chen, 2011](#); [Fallahpour et al., 2011](#); [Lee, 2012](#)) were introduced in the methods.

Difference expansion (DE) based reversible watermarking method is proposed by [Tian \(2003\)](#). In their method, the difference of two neighbor pixels is expanded to create a vacant space for embedding 1-bit information, and the maximum embedding capacity reached 0.5 bpp (bit per pixel). [Alattar \(2004\)](#) generalized the DE method by utilizing the $n-1$ differences of n neighbor pixels to embed information, thus extending the maximum embedding capacity to $(n-1)/n$ bpp. Based on DE, [Kamstra et al. \(2005\)](#) proposed a reversible watermarking method that has a better embedding efficiency by using wavelet transform and sorting. [Thodi and Rodriguez \(2007\)](#) proposed a reversible watermarking method called prediction-error expansion (PEE) which better exploits the

correlation inherent in the neighborhood of a pixel than the DE method. [Sachnev et al. \(2009\)](#) proposed a representative method of PEE which predicts the pixel by averaging the gray values of the four neighboring pixels with a rhombus shape, and the sorting technique is used to record the prediction errors based on magnitude of its local variance. This method can efficiently reduce the size of location map and embed more data with better image quality. [Coltuc \(2011\)](#) split the prediction errors into the current pixel and its prediction context, which minimizes the square error introduced by the embedding. By doing so, it introduces less distortion than the classical PEE method. However, these methods based on DE and PEE have to double the differences of neighbor pixels or the prediction errors, which often cause larger distortion for watermarked image, especially for the texture image or the texture regions of the image.

Histogram shifting (HS) based reversible watermarking method is proposed by [Ni et al. \(2006\)](#). In their method, the histogram bins between the peak and zero points are shifted one unit in the direction of zero point, hence creating an empty histogram bin to embed watermark. Although a high quality watermarked image is obtained, the embedding capacity is limited by the height of peak point. [Tsai et al. \(2009\)](#) introduced the prediction technology into HS, which solves the problem of low embedding capacity of HS by exploiting the similarity of neighboring pixels to construct a prediction error histogram. [Luo et al. \(2010\)](#) utilized the interpolation-error instead of the prediction error to embed watermark, which can embed a large amount of message into the images with imperceptible modification. [Fallahpour et al. \(2011\)](#) proposed a reversible method based on the demanded capacity and desired image quality, in which the errors of frequencies larger than the capacity are shifted. [Hong et al. \(2011\)](#) proposed a reversible method based on image interpolation and the detection of smooth and complex regions

in the host images. [Hong et al. \(2012\)](#) adopt a better predictor and employ an error energy controlled (EEC) which reduces the number of non-embeddable prediction errors. Although these methods based on PE achieve larger embedding capacity than the HS through the use of prediction or interpolation technologies, the quality of the watermarked image is not very satisfactory, because all these methods simply attempt to increase the height of the peak point, without considering to reduce the distortion for the host image in the same height, particularly the number of shifted pixels.

In this paper, we propose a novel reversible watermarking method using the multi-prediction scheme and asymmetric-histogram shifting technique, which increases the height of the peak point while reduces the number of shifted pixels. In addition, a complementary embedding strategy is proposed combining the maximum and minimum prediction errors, in which some of the watermarked distortion will be restored since the max-embedding and min-embedding have opposite shifting directions. Experiment results show that the proposed method achieves high embedding capacity with minimal visual distortion.

The rest of this paper is organized as follows. In Section 2, we introduce the basic idea of HS of prediction errors. Then in section 3, we describe the proposed reversible watermarking method in detail. Next, several experimental results are illustrated and discussed in section 4. Finally, we conclude the paper in Section 5.

2. Discussing the HS of prediction errors

In this section, we take Tsai et al.'s method as an example to introduce the details of the reversible watermarking method based on HS of prediction errors.

For a given grayscale image X of size $M \times N$, partition it into image blocks of size $n \times n$, each consisting of a center pixel (the basic pixel) and other pixels (the non-basic pixels). The procedure of watermark embedding can be summarized as follows:

(1) For each image block, calculate the prediction errors by subtracting the non-basic pixels from the basic pixel. An error histogram $h(e)$ is constructed by gathering all the prediction errors, $e \in [-255, 255]$.

(2) Divide the histogram $h(e)$ into two parts: non-negative part $h(e_+)$ and negative part $h(e_-)$, where $e_+ \in [0, 255]$, $e_- \in [-255, -1]$, and then obtain two pairs of peak and zero points (P_+, Z_+) and (P_-, Z_-) .

(3) Modify the histograms $h(e_+)$ and $h(e_-)$ to embed watermark for the above two embedding pairs using HS method.

(4) For each image block, calculate the watermarked values by subtracting the modified prediction errors corresponding to each value from the basic pixel, and the watermarked image is obtained.

At the receiving end, the watermark extraction and image recovery procedures are similar to that of the embedding, thus the details have been omitted for brevity.

In Tsai's method, both the histograms $h(e_+)$ and $h(e_-)$ are used for embedding, so the embedding capacity is approximate to $h(P_+) + h(P_-)$. However, the entire host image are modified except for those pixels at peak points with "0" embedded, which will cause a huge distortion in watermarked image, for example in Elaine, 190015 pixels are shifted when setting $P_+ = 0$ and $P_- = -1$. Even if only one peak point is used, about half pixels of the host image will be shifted since the error histogram usually resembles a Laplace distribution with mean zero (see Fig.1). In Elaine, 104988 pixels

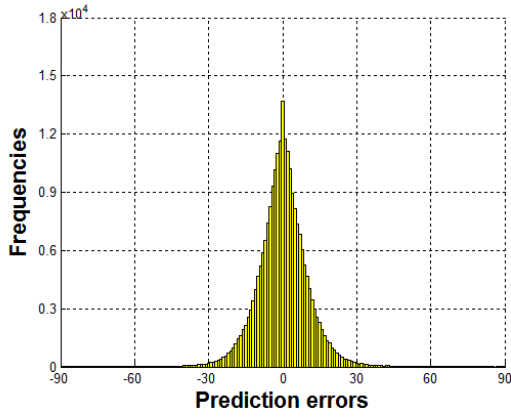


Fig.1. Prediction error histogram of Elaine image using Tsai's method.

are shifted when only $P_+ = 0$ is used. Thus, constructing an asymmetric error histogram and then shifting it in the direction of less data are very useful for reducing the shifting distortion.

3. Proposed method

In this section, we will first introduce the creation process of asymmetric error histogram, and then embed watermark using HS technique, finally a complementary embedding strategy is proposed using the dual prediction errors.

3.1 Procedure for creating an asymmetric error histogram

In traditional reversible watermarking method based on the prediction errors, the single-prediction scheme (SPS) is used, which calculates one prediction value for the current pixel such as MED. In this paper, we design a multi-prediction scheme (MPS)

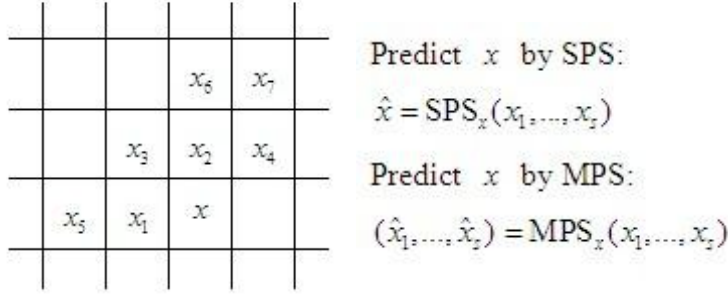


Fig.2. Context for predicting the current pixel x .

which predicts multiple values for the current pixel (see Fig. 2). An asymmetric error histogram is then constructed by using an asymmetric selection function (see Definition 1) to select the suitable prediction errors. The detailed procedure is listed as follows:

Firstly, calculate the prediction values of the current pixel x by previously visited reference pixels x_i , where $i = 1, \dots, s$, and then s number of prediction values \hat{x}_i can be obtained by modifying or reselecting the prediction algorithms used. The prediction errors \hat{e}_i are calculated by:

$$\hat{e}_i = x - \hat{x}_i, i = 1, \dots, s. \quad (1)$$

From the second row and column, x has at least three reference pixels (left x_1 , upper x_2 and upper left x_3), so we have $s \geq 3$.

Secondly, select a suitable one from the above errors \hat{e}_i by the following formula:

$$e = f(\hat{e}_i), i = 1, \dots, s. \quad (2)$$

where f is an asymmetric selection function which is defined as below.

Definition 1: For a matrix $M = [C_1, C_2, \dots, C_n] = [R_1, R_2, \dots, R_s]^T$, where each C_i is a column array, R_j is a row array and obeys a symmetric distribution with mean zero, we

said f is an asymmetric selection function, if the array $R = \{c_i \mid c_i = f(C_i), i = 1, \dots, n\}$ does not obey a symmetric distribution. For example, the maximum and minimum functions ($\max(\cdot)$ and $\min(\cdot)$) are the simplest asymmetric selection functions.

Finally, after calculating all selected errors, e , in the entire host image, gather them together and then an asymmetric error histogram could be constructed.

This paper focuses on the analysis of a new perspective in reversible watermarking research, so we adopt the simplest prediction algorithm-nearest neighbor prediction (NNP) and select the lower bound to be $s = 3$ in the following sections. However, the proposed method does not rely on the concrete prediction algorithm, and a better performance will be achieved if an excellent prediction algorithm is to be used.

3.2 Embedding procedure

For an 8-bit grayscale image X of size $M \times N$, let x_{ij} denote the pixel value of the row i column j , and we have $x_{ij} \in [0, 255]$. During embedding, the overflow/underflow problem might occur because pixels valued 0 and 255 might be changed to -1 and 256, respectively. To solve this problem, the location map method is used as follows: scan the image X line-by-line from the second row and column, once the pixel valued “1” (or “254”) is encountered, assign a “0” in the location map L ; if the pixel valued “0” (or “255”) is encountered, modify its value to “1” (or “254”) and assign a “1” in L . After all pixels are processed, append L to the end of the watermark. The embedding procedure is described as follows:

- 1) Pick pixels on first row and column as the reference pixels. In the NNP algorithm, the prediction value is calculated by the nearest neighbor pixel and both have the same

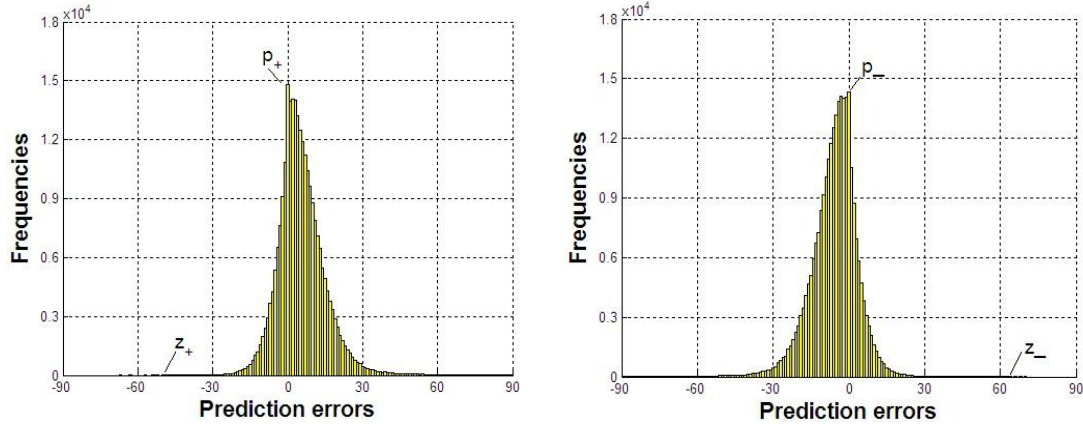


Fig.3. Asymmetric-histograms $h_+(e)$ and $h_-(e)$ of Elaine image.

values, thus for $2 \leq i \leq M, 2 \leq j \leq N$, the pixel x_{ij} is predicted by the previously visited left, upper and upper left pixels $x_{i,j-1}, x_{i-1,j}$ and $x_{i-1,j-1}$. Hence the left, upper and upper left prediction errors el_{ij}, eu_{ij} and ed_{ij} respectively are calculated by:

$$\begin{cases} el_{ij} = x_{ij} - x_{i,j-1} \\ eu_{ij} = x_{ij} - x_{i-1,j} \\ ed_{ij} = x_{ij} - x_{i-1,j-1} \end{cases} \quad (3)$$

2) If $\max(\cdot)$ is selected to be the asymmetric selection function, the maximum prediction errors e_{ij}^+ are calculated by:

$$e_{ij}^+ = \max(el_{ij}, eu_{ij}, ed_{ij}) \quad (4)$$

So an asymmetric-histogram $h_+(e)$ is constructed by gathering all values e_{ij}^+ , as shown in Fig.3 (left) when denote the peak point as P_+ and its left zero point as Z_+ .

3) Scan the image X again and then embed watermark using the HS technique, for x_{ij} , the watermarked pixel y_{ij} with the embedded bit w can be formulated as:

$$y_{ij} = \begin{cases} x_{ij} - 1, & \text{if } Z_+ < e_{ij}^+ < P_+ \\ x_{ij} - w, & \text{if } e_{ij}^+ = P_+ \\ x_{ij}, & \text{otherwise} \end{cases} \quad (5)$$

Similarly, if select $\min(\cdot)$ as the asymmetric selection function, the minimum prediction errors e_{ij}^- are calculated by:

$$e_{ij}^- = \min(el_{ij}, eu_{ij}, ed_{ij}) \quad (6)$$

We could construct an asymmetric-histogram $h_-(e)$, as shown in Fig.3 (right) when denote the peak point as P_- and its right zero point as Z_- , for x_{ij} , the watermarked pixel y_{ij} with the embedded bit w can be formulated as:

$$y_{ij} = \begin{cases} x_{ij} + 1, & \text{if } P_- < e_{ij}^- < Z_- \\ x_{ij} + w, & \text{if } e_{ij}^- = P_- \\ x_{ij}, & \text{otherwise} \end{cases} \quad (7)$$

Take $h_+(e)$ as an example, let nl be the number of pixels to the left of the peak point, and nr is the number of pixels to the right. Namely,

$$\begin{cases} nl = \sum_{e=Z_+}^{P_+-1} h_+(e) \\ nr = \sum_{e=P_++1}^{255} h_+(e) \end{cases} \quad (8)$$

It is obvious that the number of the shifted pixels is nl using $h_+(e)$ to embed watermark, whereas the number is about $\frac{1}{2}(nl + nr)$ using traditional symmetric histogram. As $nl < nr$, $nl < \frac{1}{2}(nl + nr)$ and thus the asymmetric-histogram performs better than the traditional symmetric histogram in terms of image quality.

3.3 Complementary embedding strategy using dual prediction errors

As can be seen from the section 3.2, the error histograms $h_+(e)$ and $h_-(e)$ shift in the opposite directions, which means that pixel values are modified -1 and +1 respectively during the embedding. Therefore, we believe that both the embedding

capacity and image quality could be further improved when $h_+(e)$ and $h_-(e)$ are combined together to embed watermark. For example, $h_+(e)$ is used first to embed and then $h_-(e)$, which will in turn reduce then increase the pixel value by 1, thus the pixel is restored to its original value. Of course, first using $h_-(e)$ and then $h_+(e)$ can achieve the same effect. For simplicity, we just use the example where $h_+(e)$ is used before $h_-(e)$ to introduce the watermark embedding and extraction. The detailed embedding procedure is listed below:

Input: Host image X , the watermark W_1 and W_2 .

Output: Watermarked image Z with pixel values z_{ij} .

(1) Initialize the first row and column of Y and Z by the first row and column of X , then obtain the location map L and append it to the end of W_2 with the processing in section 3.2.

(2) For $2 \leq i \leq M, 2 \leq j \leq N$, calculate the prediction values of pixel x_{ij} , the prediction errors $el_{ij}, eu_{ij}, ed_{ij}$ and the maximum error e_{ij}^+ respectively, then obtain the image Y with the pixel value y_{ij} after all bits in W_1 are embedded, as described in section 3.2. We call this the max-embedding phase.

(3) For $2 \leq i \leq M, 2 \leq j \leq N$, obtain the prediction values of pixel y_{ij} by the reference pixels $x_{i,j-1}, x_{i-1,j}$ and $x_{i-1,j-1}$, then calculate the prediction errors $el'_{ij}, eu'_{ij}, ed'_{ij}$, the minimum error e_{ij}^- and embed message bit w_2 for y_{ij} using the formula (3), (6) and (7) respectively. Finally, obtain the watermarked image Z with the pixel value z_{ij} after all bits in W_2 and L are embedded. We call this the min-embedding phase.

To extract the embedded watermark and restore the watermarked image to its original image, a similar procedure is described as follows:

Input: Watermarked image Z , two pairs of embedding points (P_+, Z_+) and (P_-, Z_-) .

Output: Recovered original image X and the watermark W_1 and W_2 .

(1) Initialize the first row and column of X and Y by the first row and column of Z . For $2 \leq i \leq M, 2 \leq j \leq N$, calculate the prediction values of pixel z_{ij} by the reference pixels $x_{i,j-1}, x_{i-1,j}$ and $x_{i-1,j-1}$, then obtain the prediction errors $el'_{ij}, eu'_{ij}, ed'_{ij}$ and the minimum error e_{ij}^- using the formula (3) and (6), respectively.

(2) Extract the watermark w_2 with the HS technique using the following formula:

$$w_2 = \begin{cases} 0, & \text{if } e_{ij}^- = P_- \\ 1, & \text{if } e_{ij}^- = P_- + 1 \end{cases} \quad (9)$$

Thus the y_{ij} can be restored by the following formula:

$$y_{ij} = \begin{cases} z_{ij} - 1, & \text{if } P_- < e_{ij}^- \leq Z_- \\ z_{ij}, & \text{otherwise} \end{cases} \quad (10)$$

(3) Calculate the prediction values of pixel y_{ij} by the reference pixels $x_{i,j-1}, x_{i-1,j}$ and $x_{i-1,j-1}$, then obtain the prediction errors $el_{ij}, eu_{ij}, ed_{ij}$ and the maximum error e_{ij}^+ using the formula (3) and (4), respectively.

(4) Extract the watermark w_1 with the HS technique using the following formula:

$$w_1 = \begin{cases} 0, & \text{if } e_{ij}^+ = P_+ \\ 1, & \text{if } e_{ij}^+ = P_+ - 1 \end{cases} \quad (11)$$

The pixel value x_{ij} can be restored by using the following formula:

$$x_{ij} = \begin{cases} y_{ij} + 1, & \text{if } Z_+ \leq e_{ij}^+ < P_+ \\ y_{ij}, & \text{otherwise} \end{cases} \quad (12)$$

(5) After all bits in W_1 and W_2 are extracted, calculate the number of pixels valued 1 and 254 in the restored image from the second row and column and denote it by l , then gather l bits from the end of W_2 , which is the location map L . Finally, by performing the reverse of the creating location map process, the original image X is recovered.

4. Experimental results

Several experiments were conducted to evaluate the performance of the proposed method. Six common grayscale images sized 512×512 were used, which obtained from [Image database 1](#), as shown in [Fig.4](#). Moreover, in order to reduce the influence caused by the random selection of test images, 200 images from [Image databases NRCS](#) and [FreeFoto](#) are also tested, respectively, for an average result.

4.1 Comparison of the symmetric and asymmetric histogram

As we all know, the distortion of watermarked image can be divided into two groups using HS technique: one is the embedding distortion when the embedded bit is “1”; the other is the shifting distortion which is caused by creating extra space for embedding, but the vast majority are the latter. Denote by \mathfrak{R} the indicator of the shifting distortion to estimate the efficiency of the asymmetric-histogram and calculate it as follows:

$$\mathfrak{R} = \frac{\text{the quantity of the shifted pixel (QS)}}{\text{the embedding capacity (EC)}}. \quad (13)$$



Fig.4. Test images: Lena, Peppers, Jet, Boat, Elaine and Baboon.

\mathfrak{R} indicates the number of the shifted pixels for embedding 1-bit information. The less the value of \mathfrak{R} , the less the shifted pixels. Hence there is less distortion, leading to better image quality.

Table 1 shows the comparison of \mathfrak{R} , EC and PSNR with the classical symmetric histogram-Tsai et al.'s method for one pair and two pairs embedding points (1-EP and 2-EP). As can be seen in Table 1, the proposed method outperforms Tsai's method in terms of \mathfrak{R} , EC and PSNR for various test images. Take Elaine as an example, when embedding 1-bit information for 1-EP, Tsai's method needs to modify 7.95 pixels, whereas ours only needs to modify 4.09 pixels. Further, with the increase of the embedding pairs, the shifting distortion (\mathfrak{R}) isn't increased sharply in the proposed method, which is benefited from the restoration effects of the complementary strategy.

Table 1

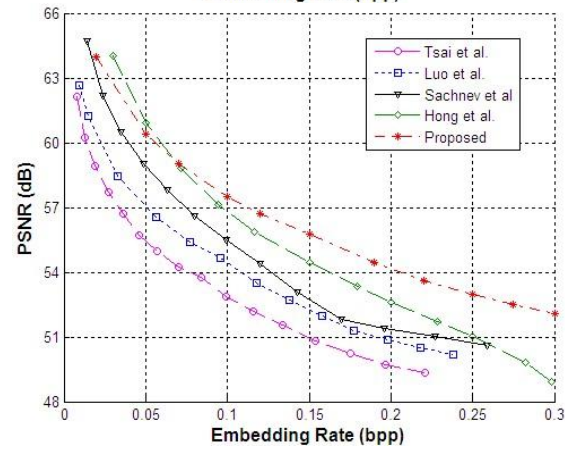
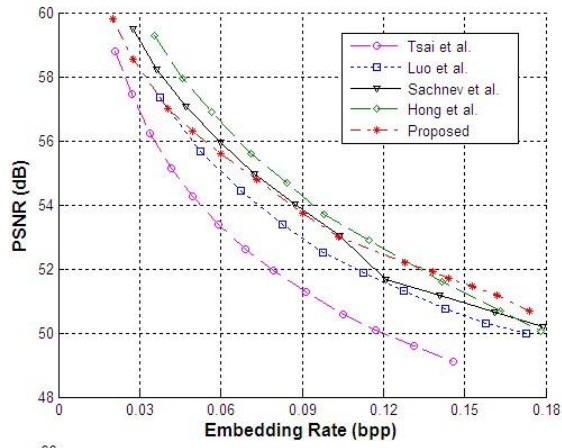
Comparison of symmetric and asymmetric histogram with different pairs.

Test image	Tsai's (1-EP)			Max-embedding			Tsai's (2-EP)			Com-embedding		
	\Re	EC	PSNR	\Re	EC	PSNR	\Re	EC	PSNR	\Re	EC	PSNR
Peppers	6.60	16246	51.70	4.68	19809	52.21	6.72	31986	48.99	3.47	36892	49.56
Lena	5.25	20126	51.68	4.01	24844	51.74	5.45	38764	49.06	5.34	45613	50.68
Elaine	7.95	13716	51.67	4.09	14819	53.90	8.57	25371	48.92	5.49	28312	50.01
Boat	4.93	21442	51.66	3.02	26531	52.63	4.62	41136	48.91	3.18	34079	50.99
Baboon	17.5	6394	51.72	12.5	8176	52.05	17.4	12588	48.76	10.2	15807	50.33
Jet	1.41	58365	51.70	0.60	64818	53.77	2.81	60728	49.29	1.01	78643	52.06
NRCS	6.68	22073	51.69	2.74	26720	52.98	7.93	38358	49.08	3.84	48497	50.48
FreeFoto	3.97	28376	51.69	1.55	34399	53.72	4.48	48137	49.18	1.59	71548	50.83

4.2 Comparison of embedding capacity and image quality

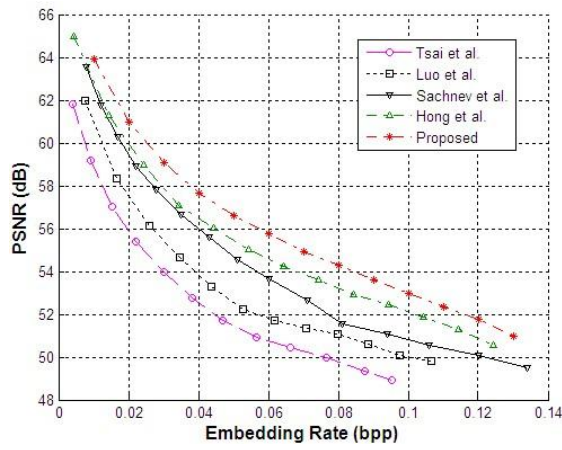
The aim of the proposed method is to provide a novel perspective for reversible watermarking research by reducing the shifting distortion, but with the increase of embedding layer, the overlapping issue tends to be serious, and the restoration effect of the complementary strategy would be weakened because it becomes difficult to select the suitable embedding points. Therefore, only single-layer embedding is considered in the experiment.

Fig.5 (a)-(f) are the comparisons of the proposed method with Tsai et al.'s, Luo et al.'s, Sachnev et al.'s and Hong et al. 2012's methods under various payloads. In Tsai et

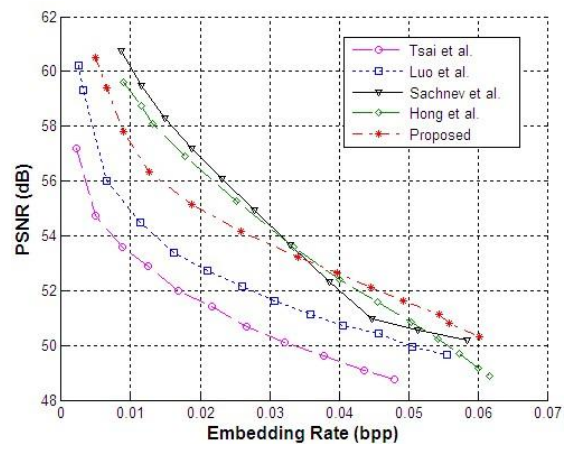


(a) Test image Lena.

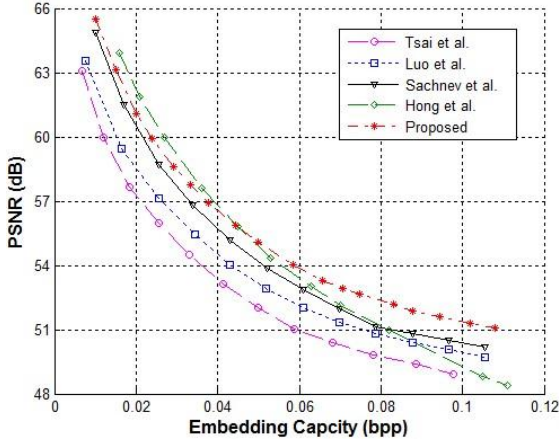
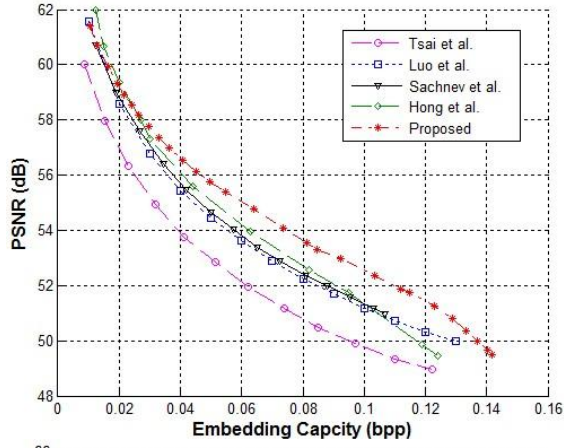
(b) Test image Jet.



(c) Test image Boat.



(d) Test image Baboon.



(e) Test image Peppers.

(f) Test image Elaine.

Fig. 5. (a-f) Comparison of the capacity and PSNR.

al.'s method, the block size is set to 3×3 , and in the proposed method, we vary the embedding points to obtain the embedding capacity-image quality curves.

As can be seen from Fig.5 (a)-(f), the proposed method has better performance than Tsai et al.'s and Luo et al.'s methods for various payloads. While compared with Sachnev et al.'s and Hong et al.'s methods, the proposed method has both advantages and disadvantages. Take the smooth image Jet and texture image Baboon as example, the PSNR of Jet of the proposed method is around 54 dB at 0.2 bpp; whereas only below 53 dB can be obtained in Sachnev et al.'s and Hong et al.'s methods. For Baboon,

the two methods perform better than the proposed method when the embedding rates less than 0.125 and 0.035 bpp, respectively. The main reason is that in the proposed method, some simplified operations are adopted to have a better extendibility, such as the lower bound of $s = 3$, NNP algorithm and without threshold. While in Sachnev et al.'s and Hong et al.'s methods, the rhombus and MED prediction algorithms were be used, these algorithms with more accurate have a better performance, especially for the texture image. And besides, the best threshold was set for the given payload to achieve the best image quality in the two methods. However, the performance of the proposed method can be enhanced by setting threshold and reselecting the prediction scheme. For example, if we use the EEC of Hong 2012's, the PSNR of the Baboon image is 54.5 dB at 0.03 bpp, which is better than that of Sachnev et al.'s and Hong et al.'s method.

We can also find that from Fig.5, compared with the other methods, the proposed method achieves a better performance at high embedding rates, while it is weak at low embedding rates. There are two reasons for this: the first being that at high embedding rates, some pixels, which were modified in the max-embedding, are restored to their original values in the min-embedding, while it becomes less efficient at low embedding rates. For example, for Lena, 12148 pixels are restored by the min-embedding at 0.176 bpp, while there is no pixel to be restored at 0.058 bpp; the second being that the shape of the shifted side of error histogram is concave, the less the height of the embedded points, the less the embedding efficiency (the bigger the value of \mathfrak{R}), thus the quality of watermarked image is degraded. At low embedding rates, the quality will be improved if select the peak points as the fixed embedding points, but the assistant information, which includes the length or the end position of the embedding, need to be sent to the receiver.

5. Conclusions

This paper presents a novel reversible watermarking method based on HS and image prediction technique. In the proposed method, a multi-prediction scheme is designed and then an asymmetric-histogram is constructed by the asymmetric selection function, which reduces the number of shifted pixels. Besides, a complementary embedding strategy using the dual prediction errors is proposed, in which the pixels shift in the opposite directions and some of the modified pixels are restored to their original values during the next embedding. Thus, the proposed method achieves better image quality. As the overlapping matter will occur in multi-layer embedding, a more powerful image prediction algorithm with multi-layer embedding will be worth investigating further.

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